Fibre-optic sensors for temperature, pressure and flow measurement

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In this paper, the use of fibre-optic techniques for measurement of the important parameters, temperature, pressure and fluid flow, especially blood flow, is reviewed. The characteristics of these devices are described and their applicability discussed.

Introduction

The making of accurate measurements of many parameters is of fundamental importance to all sectors of modern industry. A wide variety of instrumentation is available to the modern engineer and it is of importance to know the acceptability of a piece of instrumentation in a particular environment – principally in terms of the error obtained in the measurement made – to provide information having a high degreee of fidelity.

Fibre-optic instrumentation has grown out of the development of the technology of optical fibres as media for long-distance communications. In itself, this is not a drawback as many major advances in measurement technology have resulted from a 'spin-off' from more general technological achievement, e g, space advances, lasers, modern electronics, etc. The development of optical-fibre sensor systems has attracted considerable research interest over the last few years and their application in certain industrial and military environments appears very attractive due to some advantages they possess over conventional instrumentation.

Optical transducers may be conveniently classified either in terms of those devices where the fibre itself is the sensing medium or those where the fibre acts to guide light to and from the transducer element. In the former case, the transmission characteristics of the fibre are modified by the action of the external effect; in the latter, the interaction occurs only in the sensing element. A variation on this second type is the use of a non-optical primary transducer, the output of which serves as an input to an optical transmission system.

Some of the major advantages of optical sensors are that they are intrinsically free from electromagnetic interference and have good electrical isolation. Also that they can operate in hazardous environments, e g high temperatures, chemical and explosion risk areas and in biological and clinical environments due to their essentially passive mode of operation. Of great importance in the industrial context is the possibility of the use of a common fibre-optic communication link for sensor and telecommunication applications; with digital outputs from the sensor and optical multiplexing, a sophisticated yet essentially simple network can be achieved, with maximum information transfer.

Optical fibres

The term 'optical fibre' describes a certain type of dielectric waveguide for guiding light waves. As a result of their filamentary appearance, they are termed fibres. Two types of optical fibre are generally available, one whose index of refraction obeys a square law in the radial direction and the more common type where the index change occurs abruptly, as in the cladded fibre. Here a dielectric cylinder of index n_1 is surrounded by a concentric dielectric cylinder of index n_2, where the relation $n_1 > n_2$ is obeyed. Transmission along the fibre occurs through total internal reflection at the dielectric media interface.

The use of this phenomenon for transmission of light has been known for some considerable time and was demonstrated by Tyndall in 1870. The major problems of a practical communication system based on this phenomenon were overcome in 1954 with the proposal of a cladded fibre, although serious problems of attenuation remained. In a cladded fibre, the core is always surrounded by a medium of known and constant refractive index and, since the core of the fibre must be supported, it is advantageous to surround the inner core region with the cladding to avoid scattering and field distortion by the supporting mechanism coming in contact with the guided field. Secondly, to permit the construction of fibres in which only one guided mode may propagate with an achievable inner core diameter, the ratio of n_1/n_2 must be carefully chosen. The larger the ratio the smaller must be the diameter of the core. When the ratio is near unity, the inner core may be several micrometres in diameter and still permit single-mode operation.

A comprehensive discussion of the propagation of light in fibres, is contained in Marcuse (1982). Such single-mode fibres have application in telecommunications and some specialised sensors. It is fortunate, for ease of coupling of light to fibres, that larger diameter (e g, $100 \leq d \leq 1000\,\mu m$) fibres may be used for most of the sensors to be described.

The success in the reduction of the attenuation of light transmitted in optical fibres has ensured their applicability for information communication. Early fibres had attenuations of ~ 100 dB/km but today figures of ~ 0.2 dB/km are achievable for near infrared transmission, with improvements regularly being announced by major manufacturers. Such low attenuation makes possible multi-kilometre lengths of data communication links. Fundamental limits of intrinsic losses are being reached.

The wavelength dependence of these losses is illustrated in Fig 1. These are due to Rayleigh scattering from disorder in a typical glass-fibre material which may be structural or compositional. In the former, the basic molecular units are connected in a random way, whereas in the latter, the composition may vary from place to place. The net effect is a refractive index change and if each irregularity is of size

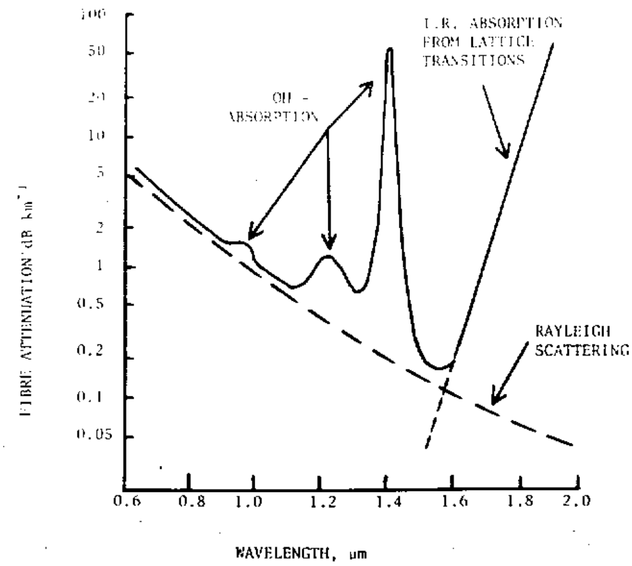


Fig 1 Typical attenuation vs wavelength plot for a silica-based optical fibre

$\sim\lambda/10$ it will act as a scattering centre. The absorption coefficient from Rayleigh scattering will have a λ^{-4} dependence. This defines the minimum loss attainable in a fibre. Absorption losses, on the other hand, are mainly due to the presence of impurities, eg, Fe^{3+}, Cu^{2+} or OH^- ions (the latter arising from the presence of water and having distinctive peaks at 0.95, 1.24 and 1.39 μm).

It has been the success in manufacturing fibres to such a high degree of purity which has reduced these impurity losses. Beyond 1.6 μm the main losses are due to transitions between vibrational states of the lattice. Distortion of the fibre from the ideal straight line configuration will lead to so-called 'bending losses'. For example, to maintain a plane wavefront at a bend, a part of the mode may have to travel at velocities greater than light in the medium. As this is impossible, part of the mode is lost through radiation. Such losses are greater for bends of small radius and for modes which extend most into the cladding. Hence sharp bends are to be avoided, although this phenomenon may be used in certain sensors.

Fibres may be manufactured from a number of materials but the most practical are plastics and glasses. The former have some manufacturing and cost advantages, but their much higher attenuation limits their useful length. Most high-quality applications use fibres manufactured from various glasses.

Of the light sources available with a directional output for ease of coupling to the fibre, the most important are the small, low-voltage yet bright light-emitting diode (LED) and the laser. A range of wavelengths is available in pulsed or continuous wave output from existing devices to suit the specific application and fibre. Sensitive detectors such as the silicon p-i-n photodiode and avalanche photodiode may be used, or alternatively high-voltage photomultiplier detection. However, the use of convenient low-voltage emitters and detectors is to be preferred in many industrial applications where small size, light weight and robustness are required.

In this paper, some of the methods available to measure a number of important parameters – temperature, pressure and flow velocity, especially the flow of blood in clinical situations – are presented, together with comment on their suitability and possible improvement. The approach has been to consider the measurand rather than the technique as has primarily been the case in a number of previous reviews (Culshaw, 1982; Yao and Asawa, 1983; Giallorenzi, 1981). It does not claim to be fully comprehensive but illustrative of the impact that fibre-optic technology is having upon measurement and instrumentation today.

Fibre-optic temperature sensors

There are several variations of this type of sensor utilising a number of transducer materials and concepts, or even the use of the fibre itself as a temperature sensor. In this latter case a temperature change ΔT can introduce a phase shift $\Delta\phi$ in the light propagating in the fibre, and this can be detected interferometrically. This is given by (Corke *et al*, 1983):

$$\frac{\Delta\phi}{\Delta T} = \frac{2\pi L}{\lambda}\left(\frac{n}{L}\frac{dL}{dt} + \frac{dn}{dT}\right) \qquad \ldots (1)$$

where L is the fibre length,
n is the medium refractive index, and
λ is the light wavelength, at temperature T.

For fused silica, the index change (dn/dT) is dominant, contributing over 95% of the thermally induced phase shift. The phase shift may be detected using a Mach–Zender or Michelson all-fibre interferometer, the latter providing a factor-of-four improvement in sensitivity. Good linearity has been achieved, and temperatures in the range – 30 to 240°C have been measured with a reported accuracy of ± 1°C, using electronic signal recovery techniques and a laser diode source.

An alternative approach is the use of the temperature effect on the structure of solid dielectric crystals, which is best sensed by probing with polarised light, conveyed to and from the sensor through optical fibres (Rogers, 1982; James *et al*, 1979), as illustrated in Fig 2. When linearly polarised light is passed into a crystalline quartz block and propagates along the crystal optic axis, it will emerge still linearly polarised but with its direction of polarisation rotated by the natural optical activity of the quartz. Hence, when light passes through the crystal, the polarisation direction is rotated through an angle r_T. Then it passes through a $\lambda/4$ plate set at an angle ϕ to the reference direction and thence to a mirror, where it comes back along its path to a polarisation analysing prism. The polarisation direction will be then at an angle (to the reference direction):

$$r_T - 2(r_T - \theta) - r_T = -2(r_T - \theta) \qquad \ldots (2)$$

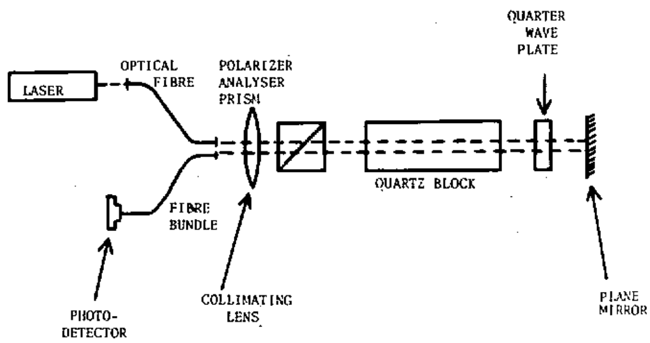


Fig 2 Optical arrangement for polarised-light quartz crystal temperature sensor

The prism passes that light amplitude component linearly polarised in its acceptance direction, and so the light power detected by a photodetector will be:

$$P_T = P_0 \cos^2 2(r_T - \theta) \qquad \ldots (3)$$

where P_0 is the incident light power.

For maximum linearity θ is set so that:

$$2(r_T - \theta) = \pi/4 \quad \text{or} \quad \theta = r_{T_c} - \pi/8$$

where r_{T_c} lies at the centre of the range of interest.

Hence, it may be deduced that, to a good approximation:

$$(P_T - P_{T_c})/P_0 = 2(r_T - r_{T_c}) \qquad \ldots (4)$$

Consequently the output will vary linearly with T, independently of drift in the laser output. Such a system provides immunity from the external longitudinal magnetic fields often present. The polarisation rotation so caused through the Faraday magneto-optic effect (Jenkins and White, 1953) produces a rotation whose sign (in contrast to that caused by optical activity) is independent of propagation direction. In response to a transverse electric field, the electrogyration effect (Rogers, 1977) is zero for light propagating parallel to the optic axis in quartz and can thus be ignored. The Pockels electro-optic effect in quartz is small and may be considered negligible in the sensor.

One of the major disadvantages of the device is the stringent requirement for the light to propagate along the optic axis of the crystal. This requires accuracy in cutting the crystal. The relative positional stability of the components of the device as the temperature varies is of critical importance, requiring precision manufacture. Also its physical size of 65 x 9 mm (Rogers, 1982) may preclude its use in certain space-limited environments. Operating in the 20–180°C range, the device had an accuracy of ~ 1%.

Another promising temperature sensor utilises the coupling of the polarised light in mixed crystals (e g, hexagonal semiconductors like ZnO and CdS) at energies below the material band gap (James *et al*, 1979). Energy is coupled from the transmitted mode (parallel to the optical axis) to the absorbing mode (perpendicular) in a manner that would not normally occur except for the crossings in the refractive index curves where $n_x = n_y$. There the anisotropic crystal becomes isotropic and the two polarised modes are easily coupled, having the same k vectors. The effect of temperature is to change the wavelength of light which can be coupled to give transmission and so this is a monitor of the temperature change. Such a device benefits from the fact that it is the wavelength itself that bears the relevant information and not its intensity. However, a wavelength selection device, such as a grating monochromator, is required for its operation. Similarly a Fabry–Perot etalon is temperature-sensitive, where the wavelength transmitted is a function of the separation of the plates constituting it. Such a separation can be temperature-dependent and so, again, the wavelength transmitted is a temperature-dependent quantity.

Temperature sensors utilising the principle of attenuation of light transmitted through a fibre have been known for some time. A device which uses the movement of a temperature-sensitive bimetal to provide a lateral shift and spoil the optical alignment between a fibre-lens connector assembly has demonstrated a 0.5% resolution for the 10–50°C range (Ishikawa *et al*, 1978). The accuracy of such a device depends critically upon a knowledge of the uninterrupted light intensity, or a transmission calibration at a known temperature.

More promising as a commercial device is the use of a temperature-sensitive transparent substance as a light attenuator.

The variation in reflectance with temperature of liquid crystals has been used for sensing in certain medical applications (Hartog and Payne, 1982) as has the temperature induced change in optical rotatory power in a binary liquid crystal mixture (Jones, 1981b). The highly temperature-dependent optical activity of a binary crystal makes possible the construction of extremely sensitive thermometers over limited temperature ranges. However, a knowledge of the effects of various parameters, e g, composition, on this rotatory power is essential for accurate use of the device (Wirdhorn and Cain, 1979), illustrated in Fig 3.

The temperature-dependent properties of semiconductors have produced an operational thermometer (Kyuma *et al*, 1983), illustrated by Fig 4. The absorption of a GaAs chip is probed at two wavelengths (0.86 and 1.3 μm) to investigate the absorption band-edge shift as the temperature increases (Kyuma *et al*, 1982) and also to provide a reference signal, largely unaffected by the temperature change of the material. Such a device has a claimed accuracy of ∓ 0.5% and has been operationally tested in a train 'on-board' transformer in the 30–90°C region (Kyuma *et al*, 1983). A similar approach by Theocharous (1983) relies upon the strong temperature-dependence of the absorption profile of the ruby glasses in combination with a backscattering technique at two wavelengths, 605 and 622.5 nm. This approach has the advantage that the reference wavelength is much closer to the wavelength near the absorption edge, thereby minimising inaccuracies from the wavelength-dependent optical connector losses and the transmission loss of the fibre. In addition, such a method has been extended to use a series of small sensors distributed along the length of an optical fibre, with a spatial resolution of 0.1 m. The monotonic increase with temperature of the scattering coefficients of liquid-core and plastic-core optical fibres has been employed by Hartog *et al* (1982). Optical time–domain reflectometry, a technique which relies upon the known propagation velocity in the fibre to gain spatial information, was used to determine temperature-induced changes in the backscatter signal at known points in the length of a fibre filled with hexachlorobuta-1,3-diene, shown in Fig 5. A measurement range of 5–80°C has been demonstrated with a spatial resolution of 1 m over a 100 m fibre length.

The use of luminescence from a hot body for temperature measurement in simple pyrometry, with the radiation coupled from the hot objects to the detector by means of optical fibres, is an elementary approach to a non-'line of sight' situation (Campbell, 1979). Inaccuracies can arise from unknown factors of emissivity and surface cleanliness.

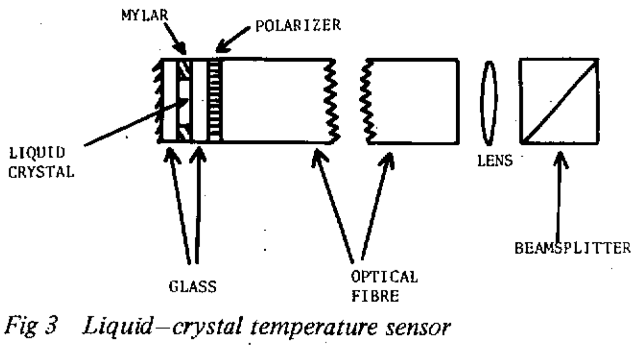


Fig 3 Liquid–crystal temperature sensor

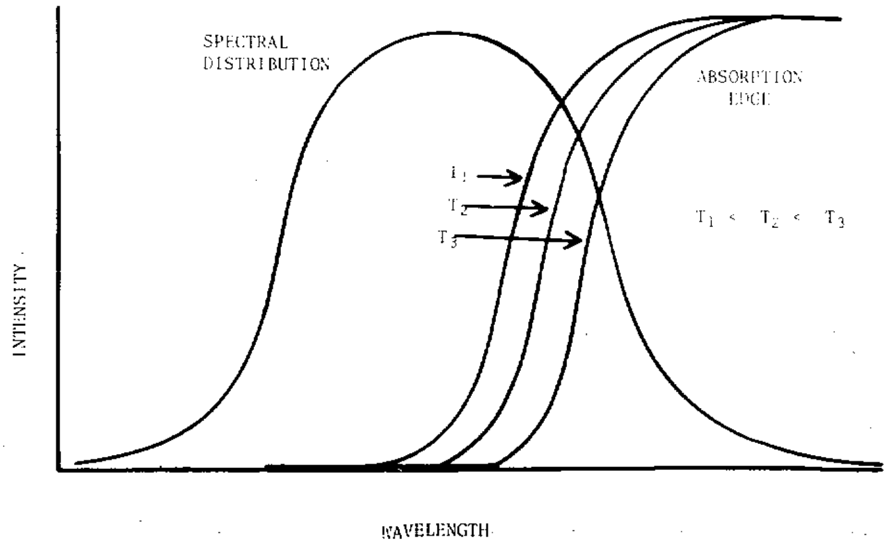


Fig 4 Characteristic of semiconductor absorption-edge temperature sensor

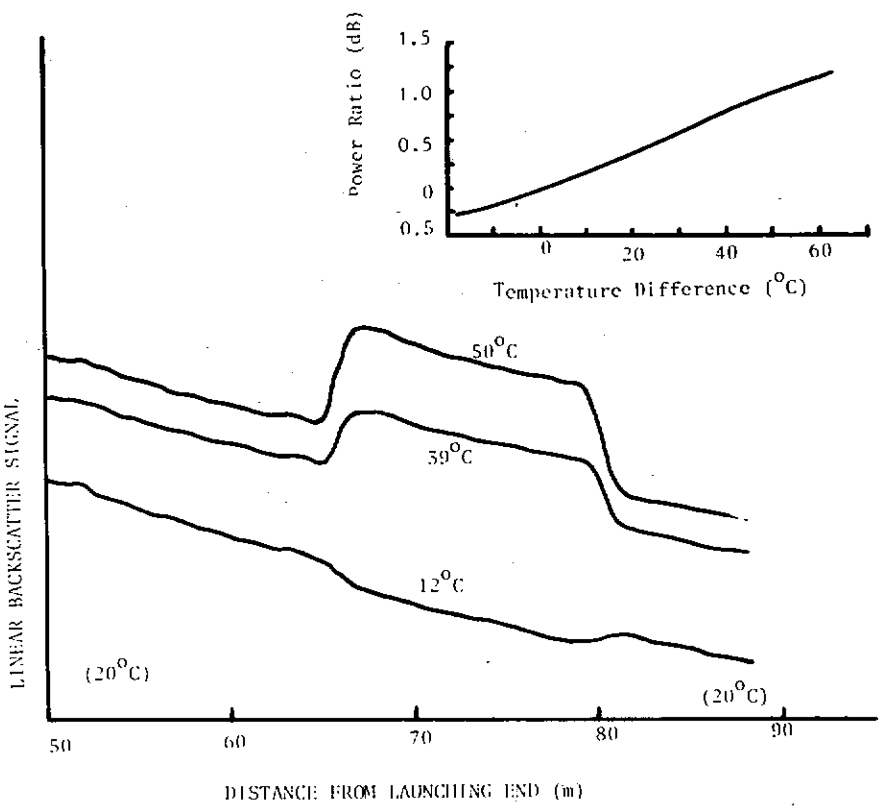


Fig 5 Output characteristic of liquid-core fibre distributed temperature sensor

Additionally, a simple sensor may be constructed based on the blackbody radiation from a heated fibre tip, the temperature being measured from the optical power received at the remote photodetector (Dakin and Kahn, 1977). Usable for higher temperatures only, a resolution of 1% over the range 400–1100°C has been demonstrated. The accuracy of such a sensor may be improved by using a two-colour detector system to sense more of the spectial shape for specialist applications, e g, finding hot spots in electrical machinery.

In contrast, by using photoluminescence, i e, the luminescence which is induced by excitation by visible or UV radiation, temperature information on the body is readily available. There are four basic characteristics of luminescense which may be exploited – the shift in wavelength of the radiation, the emission line width, the emission intensity and the excited state lifetime (or decay time). Of these, the first two require fairly high-resolution spectroscopic measurements using complex equipment, although a commercial device* using the wavelength shift of the returned light is available, with an accuracy of 1°C in the 0–200°C range. Typical line shifts or broadening are a few Ångstroms.

The latter two methods are more open to use in less expensive and simpler sensors. As an example, the intensity of emission of Eu^{3+} in YVO_4 (a narrow line at ~620 nm)

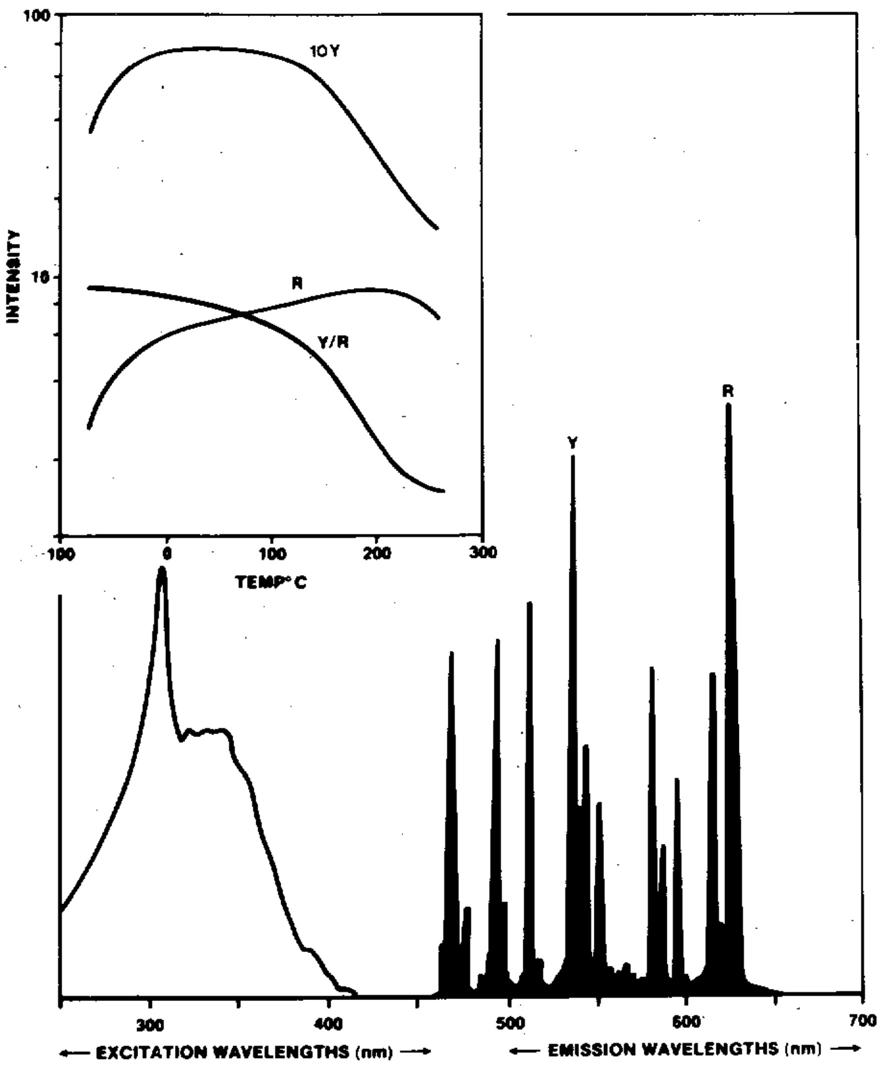
*Examples are:

(1) 'Fibre thermometer' (model 1010), by Asea Innovation, Vasteras, Sweden, and

(2) 'Fluoroptic temperature sensor', by Luxtron Co, 1060 Terra Bella Avenue, California 94043, USA.

increases up to $\sim 500^\circ C$ before temperature activated (phonon-induced) radiationless processes decrease the emission intensity. Hence, it could be used as a temperature sensor but only in either of the single-valued regions above or below $500^\circ C$ where the intensity is known either to fall or rise with temperature. However, like all intensity sensors, it requires an additional system to compensate for source fluctuations, and joints and connectors will attenuate the signal (requiring further compensation).

A second system, which overcomes some of these problems, ratios two luminescent emission at different wavelengths and hence compensates for source fluctuations. The use of a single luminescent material overcomes any problem of inaccuracies from the different rates of degradation of the active material. Again, rare-earth-doped phosphors may be used, e g, Eu^{3+} in Y_2O_2S emitting at 586 and 616 nm. This choice of wavelength reduces but does not eliminate the problem of differential attenuation of joints and connectors. Also two detection systems are required and the efficiencies of both photodetectors must be maintained at a constant value. A commercial device, the 'Luxtron' sensor based on this technique, has been available



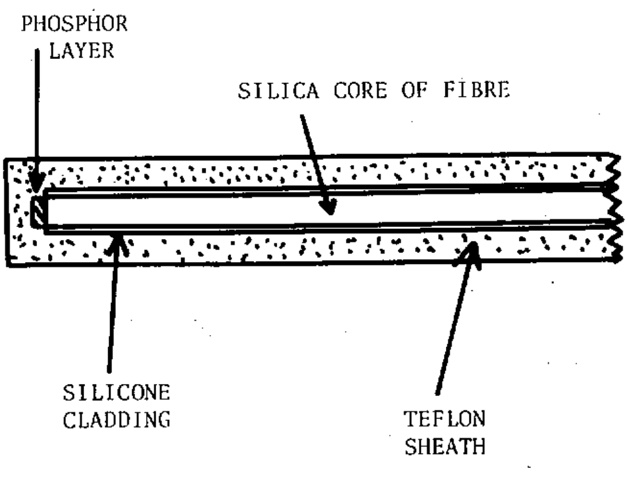


Fig 6 Schematic of 'Luxtron' temperature sensor

(see Fig 6) with a claimed accuracy of ∓0.1°C over the 30–50°C range and 1% over the range –50 to 250°C.

The most satisfactory method of sensing temperature using luminescence is via the monitoring of excited-state decay time. This principle has been successfully demonstrated using the decay of the fluorescence from Cr^{3+} ions excited by a tungsten source in ruby crystals to measure temperatures in the human body range at 40°C, as illustrated by Fig. 7. A resolution of 0.3°C was reported for the sample studied (Sholes and Small, 1980), with good temporal resolution (~4 ns), although an actual device was not constructed. Grattan *et al* (1984) have reported a working thermometer on this principle using the fluorescence from a neodymium rod excited by an infra-red LED.

When a fluorescent medium is excited, the intensity of emission, I, is related to the number of excited species, N, via:

$$I = -\mathrm{d}N/\mathrm{d}t = kN \quad \ldots (5)$$

where k is the rate constant, equal to the inverse of the observed excited-state lifetime. The rate constant is increased by increasing temperature due to the activation of competing non-radiative processes (see Fig 8). However, the natural lifetime of the species, τ_0, related to the observed lifetime τ via the fluorescent quantum efficiency, ϕ_F, by

$$\tau = \phi_F \tau_0 \quad \ldots (6)$$

is generally temperature-independent (Birks, 1970). Rare-earth ions in inorganic compounds have been used as transducers (McCormack, 1981), having high quantum efficiencies (eg, barium chlorofluoride activated by samarium, $BaClF{:}Sm^{2+}$). Under excitation from a 150 W xenon arc lamp, the emission at 687 nm was recorded to measure temperatures up to 200°C to an accuracy of ∓5°C, where an observed decay time of ~500 μs was recorded.

A possible extension of this work is the use of organic scintillators at the sensor element. In these materials, such as 9-10-diphenyl anthracene, stability at temperatures of ~300°C has been displayed with the temperature-dependence of the radiationless processes occurring within the molecule being characterised by a drop in quantum efficiency of fluorescence, ϕ_F, and reduction of observed lifetime (Compton *et al*, 1980). Indeed, the rate constant, k', for crossing from the fluorescing lowest singlet state of the molecule to the lowest triplet state, has a temperature-dependence of the form:

$$k' = k^0 + A \exp(-E/RT) \quad \ldots (7)$$

where k^0, A and R are constants, E being the state energy difference (Turro, 1978). Consequently such materials could be used as temperature sensors in the same way. Excitation in the near UV by short-pulse lasers is facilitated by strong absorption bands in this region in a number of compounds. High-intensity laser excitation can overcome the problem of stronger transmission losses of UV radiation (compared to visible and IR) by optical fibres. The much shorter decay time (~10 ns cf ~500 μs for $BaClF{:}Sm^{2+}$) combined with high fluorescence quantum efficiencies mean that such sensors could be used in a quasi-distributed thermometer, with a series of sensors connected to a single optical fibre to give high spatial resolution.

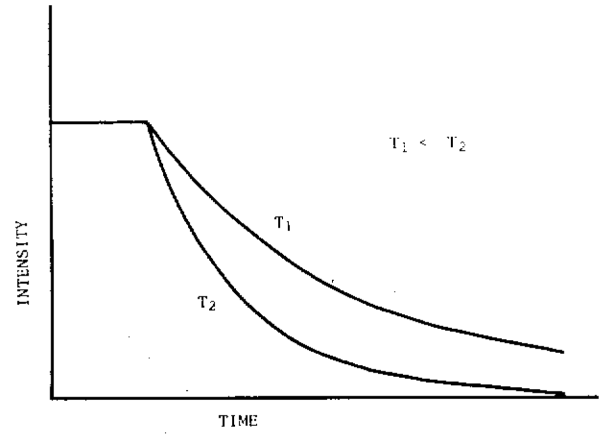


Fig 8 Schematic variation in 'decay time' with temperature.

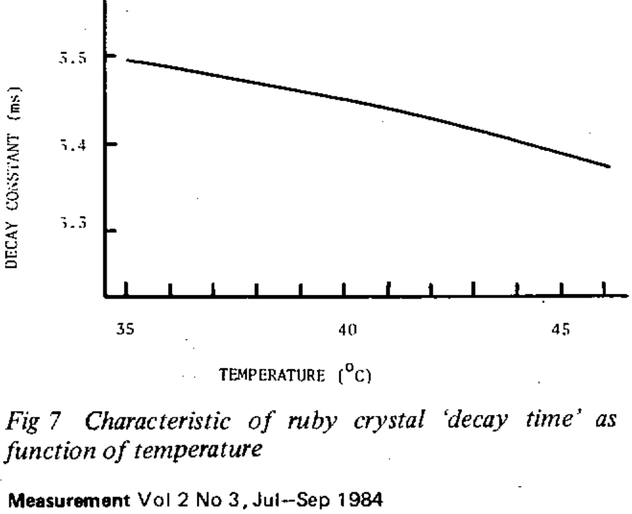


Fig 7 Characteristic of ruby crystal 'decay time' as a function of temperature

For applications where the attenuation of UV exciting radiation is too severe (eg, for very long lengths of fibres), the sensor could be an organic dye absorbing in the green region of the spectrum with red (eg, rhodamine 6G) or IR emission (eg, nile blue perchlorate). The end of the fibre could be coated with the dye or encapsulated in a transparent plastic (eg, polymethyl methylacrylate (PMMA)). This would inevitably reduce the observed fluorescence lifetime but the temperature-dependence could still be detected. Other luminescent phosphors could be used (eg, $CaAl_2O_4{:}Eu$) having shorter observed lifetimes (Tyner and Drickamer, 1977a) than $BaClF{:}Sm^{2+}$ (McCormack, 1981). Indeed, the strong pressure-dependence of the observed lifetime of this phosphor could lead to a sensor with a pressure and temperature transducer or, indeed, a series of such different sensors connected by a single optical fibre. For example, the observed decay time of $CaAl_2O_4{:}Eu$ (Tyner and Drickamer, 1977b), is comparatively pressure-insensitive over the 0.70 kbar region at a fixed temperature, while that of $CdMoO_4$ varies from 1.8 to 0.4 μs over the same pressure region, at room temperature. In either case, the advantages of the decay-time measurement system remain: the lifetime is intrinsically independent of the initial intensity and only one wavelength region need be detected.

Fibre-optic pressure sensors

The value of the pressure applied to a material may be determined from the measurement of the displacement of a sensing element and, indeed, a number of displacement measuring devices have been described in the literature (Jones, 1981a). However, conversion from a measure of

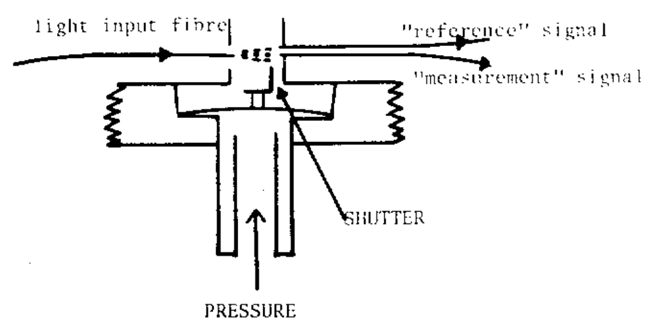


Fig 9 Schematic 'shutter' pressure sensor

displacement to pressure may be expensive in practice and introduce errors through the transformation. A number of the techniques described in the previous section on temperature measurement may be applied to the determination of pressure (e g, the change of spacing of the plates of the Fabry–Perot etalon and the variation in the 'decay-time' of luminescent materials). It is obvious that, even from these examples cited, the choice of sensor will be strongly influenced by the value of the pressure to be measured, the former example being sensitive to small pressure values and the latter particularly useful for measurements in the region of tens of kbar. Additionally, the simple shutter principle may be employed in pressure determination, the pressure applied to a diaphragm causing the movement of an opaque vane at right angles to the force direction to obscure the light from an LED source (McGowan, 1979). Another photodiode monitors the uninterrupted light to provide a reference signal. Electronic processing then enables the pressure measurement to be made. Non-linearity of ~0.6% of full scale has been reported. Although this device is not strictly a fibre-optic system, it is easy to imagine a similar construction, as shown in Fig 9, where the light from the source and to the detector is carried by optical fibres to enable a common electronic processing system to be used for a number of such detectors.

Another fundamentally simple device is the 'Fotonic pressure sensor' of Menadier *et al* (1967), which uses the distance between a reflecting diaphragm and the end of the optical fibre to modulate the light which is incident on an adjacent single or a series of return fibres surrounding the transmitting fibre. Such a scheme was used both for non-contact vibration analysis (Lagace and Kissinger, 1977) and in clinical use for pressure measurement in blood vessels (Frank, 1966). The light received as a function of distance

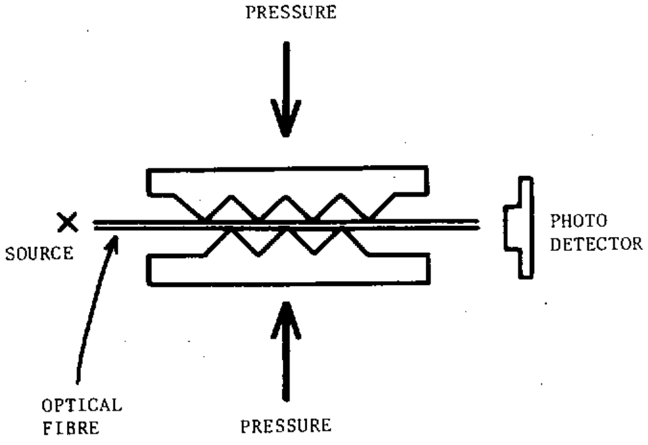


Fig 10 Schematic 'microbend' pressure sensor

(pressure) characteristic of the device shows non-linear features due to the nature of the coupling of light to the return fibres, and its magnitude will depend upon the surface reflectivity of the diaphragm. However, Tallman *et al* (1980) have demonstrated a device with only 1.4% non-linearity and 1.3% hysteresis to measure a 689 kPa pressure range.

The fibre microbend pressure sensor (Fields and Cole, 1980) shown in Fig 10 utilises the light loss in the fibre upon inducing a coupling from propagating modes to radiation modes, with consequent transmission loss. The device employs a fibre sandwiched between two ridged plates, with a periodicity depending upon the modal properties of the fibre (normally in the millimetre range). The amplitude of the bend is changed by the pressure, with a consequent transmitted intensity change.

An important advantage of this sensor is that the optical power is maintained within the fibre and the transducer mechanism is compatible with multimode fibres. Lagakos (1981) has reported a detection threshold of 60 dB re 1μPa, in a non-optimised situation, a 40 dB improvement on the previous results of Fields and Cole (1980). Jones and Spooncer (1981) have described a system where the light transmission is a function of a pressure-induced stress in a photo-elastic material (e g, epoxy resin). Using polarised light, the effects of the induced birefringence of the material are detectable with an analysing polariser. A linear output may be obtained over a limited range and a resolution of ~0.05 N for input loads in the 20–50 N range is reported. Additionally, the change in birefringence of a single-mode fibre when wrapped on a small cylinder may be used for pressure measurement (Rashleigh, 1980). A tension is obtained in the fibre coil and the birefringence is altered by the strain induced in the fibre by being wrapped on the cylinder. An appropriate analyser can convert the polarisation changes of the light travelling in the fibre to a convenient intensity measurement. Although requiring single-mode fibre for its operation, again this device has the advantage of confining the light to the fibre itself when operating.

When the cores of two fibres are nearly adjacent over a distance, light may be coupled from one core to another via the evanescent wave illustrated by Fig 11. A pressure-measuring device using such an approach can be fabricated with multimode fibres, and Beasley (1980) has demonstrated detection thresholds of 50 dB re 1μPa/(Hz)$^{1/2}$ for such a system. As with the microbend device, very accurate mechanical alignment on a sub-micron scale is necessary for the laboratory performance to be achieved in the practical model. The fibre-optic hydrophone (Spillman Jnr and Grave, 1980) uses the displacement between a fixed fibre and a free fibre, moving under the influence of a pressure wave. Such a device requires single-mode fibre for its operation, stringent mechanical tolerances to keep the two fibres initially co-axial, and parallel end surfaces.

Additionally disadvantageous is that the light is not confined to the fibre. These difficulties may limit its applicability in favour of simpler devices. The frustrated-total-internal-reflection technique (FTIR) shown in Fig 12 in essence uses the coupling between a fibre with its end polished at an angle θ to produce total internal reflection for all propagating modes and another similar fibre (Spillman and McMahon, 1980) or a glass flat (Croft *et al*, 1983) bonded to a fibre, for greater mechanical stability. If the fibre is stationary and the other element experiences a displacement, the light power coupled between the elements

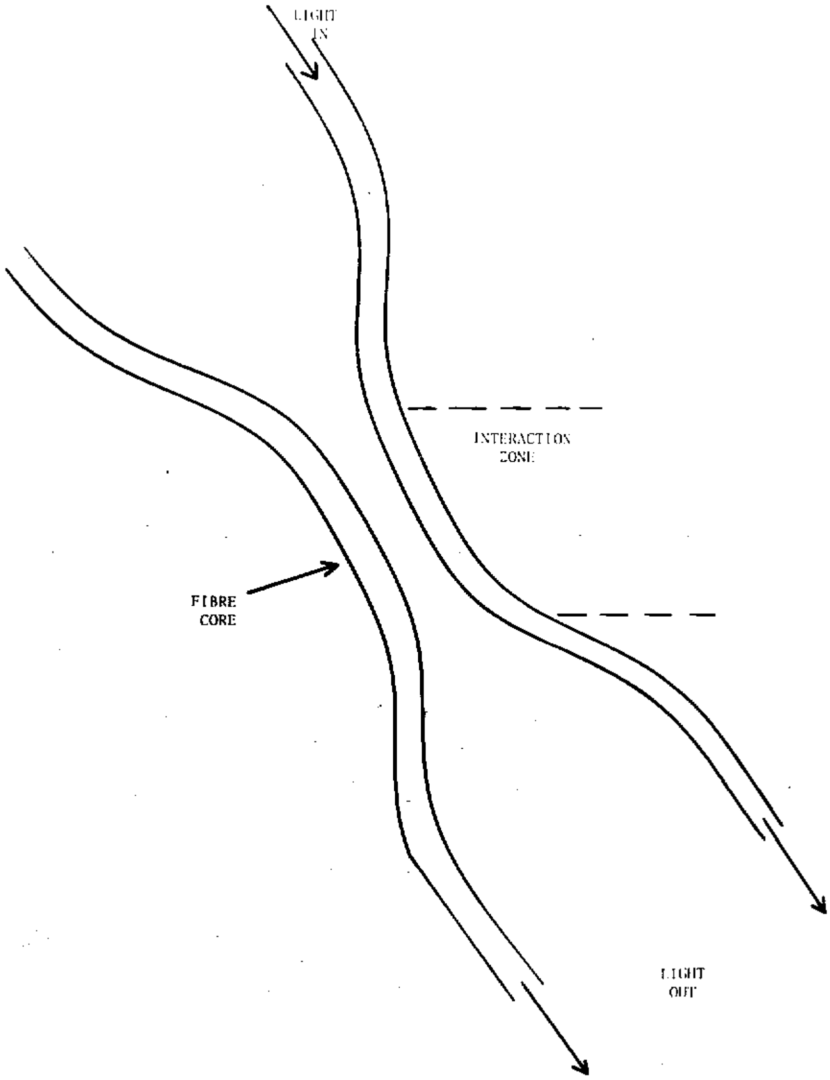


Fig 11 Schematic evanescent wave coupling for pressure sensing

varies. When detected, this gives a measure of the pressure applied to the element. Again, tight mechanical tolerances are required for field operation. Although the system suffers from the disadvantage that the light is not confined within the fibre, good detection thresholds have been demonstrated (Spillman and McMahon, 1980).

Finally, a device similar to the FTIR sensor is the near-total-internal-reflection sensor (Phillips, 1980), shown in Fig 13, employing a single-mode fibre cut at an angle just below the critical angle. The incident light is reflected back along its path by appropriate use of mirrored faces. Acoustic pressure alters the refractive index of the medium surrounding the fibre differently from that of the fibre material, causing a change of the critical angle, θ_c, to give a modulation in the light returned. Such a device has not yet been demonstrated in a fibre configuration but potentially could be fabricated. However, it does suffer from the drawback that the modulation of the returned light is very dependent on how near to the critical angle the sensor is biased, and non-linearity problems will occur near the critical angle. The use

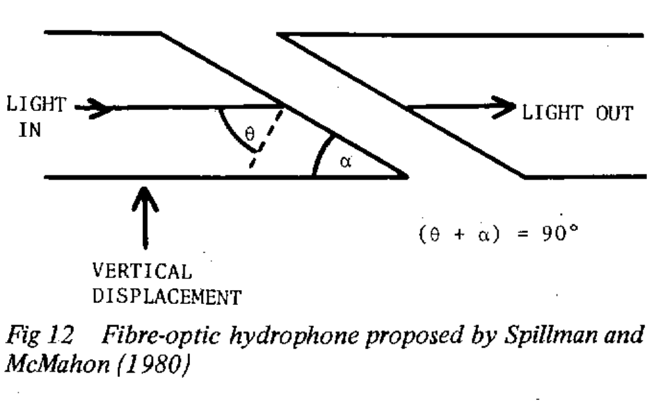


Fig 12 Fibre-optic hydrophone proposed by Spillman and McMahon (1980)

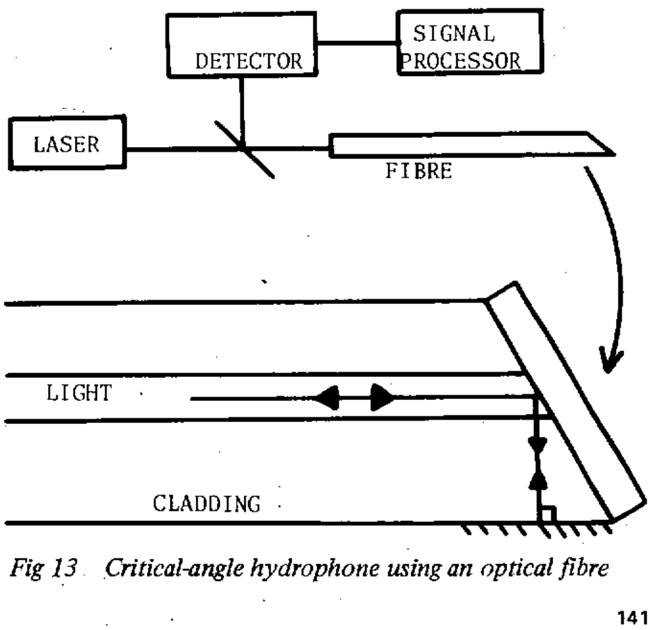


Fig 13 Critical-angle hydrophone using an optical fibre

of a frequency-tunable light source has been proposed by Phillips (1980) for use with such a sensor, due to this dependence of θ_c on wavelength (and also on the nature of the surrounding medium, through its refractive index) to ensure operation under the best conditions.

Fibre-optic flow measurement

Fibre-optic techniques for the monitoring of fluid flow have not been widely applied, and then mainly in an environment where conventional techniques are inapplicable due to the presence of hazardous materials. One such application, in the presence of flammable liquids, was the remote measurement of fluid flow (Knight, 1975). This was achieved using a light source and optical fibre linkage to measure the rotation of a shaft, as a function of the fluid flow. Additionally, opto-electronic techniques have been applied to the measurement of the vortex frequency in fluids, using the variations in the internal reflectivity of a prism mounted in the fluid (Pitt and Williamson). However, fibre optics linked to laser sources have a particular application to another environment where the use of conventional techniques may be difficult or impossible: the biological situation. Laser/fibre interferometry is non-invasive and has a wide frequency response, with good spatial resolution, enabling measurements to be taken in areas of limited access. Optical heterodyne interferometry has been applied by Noakes *et al* (1978) for the measurement of small amplitudes of motion of membrances in biological systems.

The use of laser techniques has enabled the measurement of the flow velocity of particles suspended in a liquid to be performed relatively easily. The addition of a fibre-optic facility for light transmission and reception enables such measurements to be carried out conveniently in situations where it is otherwise difficult to orientate the laser beam directly towards the particles to be studied. One of the most useful techniques is based upon the Doppler effect: the laser light is scattered from a moving particle and shifted in frequency in proportion to the velocity of the particle, the measurement of the frequency shift being made by optical heterodyning.

In this method, illustrated in Fig 14, the light scattered from the moving particles is combined with a reference beam or local oscillator on the surface of the photodetector, the latter beam being a portion of the laser beam incident on the scattering region. The photodetector mixes both signals to give an ouput with a signal fluctuating at the difference frequency.

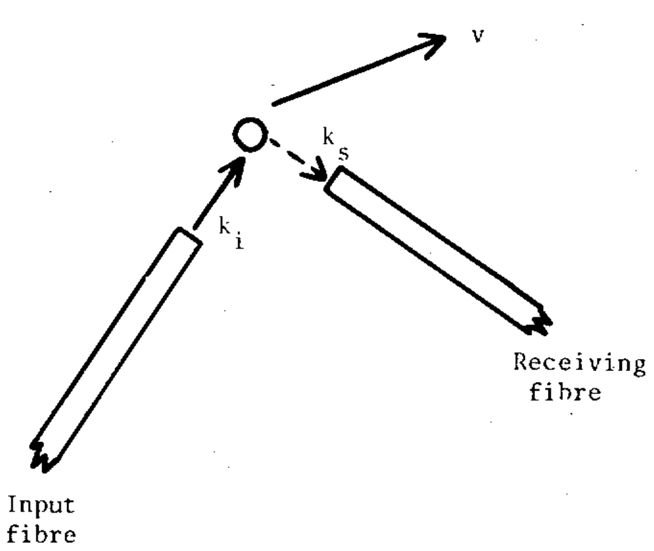


Fig 14 Schematic of laser light scattering

In general, if a particle is moving with a single velocity v, its position may be expressed as:

$$r(t) = r_0 + vt \qquad \ldots (8)$$

If illumination of this particle by a monochromatic laser light source of electric field E_i occurs, where

$$E_i = E_0(r) \exp(ik_i \cdot r i\omega_0 t) \qquad \ldots (9)$$

$E_0(r)$ being the amplitude of the field at a point $\boldsymbol{r}$, ω_0 the angular frequency and $\boldsymbol{k}_i$ the laser light wave vector, the electric field of the light scattered is:

$$E_s = Af(r)\, E_0(r) \exp\,[i(\boldsymbol{k}_s - \boldsymbol{k}_i) \cdot r(t) - i\omega_0 t] \qquad \ldots (10)$$

Here A is a constant describing the scattered field amplitude and $f(r)$ represents the fractional reduction of amplitude of light passing from the scattered to the collector. Simplifying by defining $\boldsymbol{K} = \boldsymbol{k}_s - \boldsymbol{k}_i$ and using Eqn (8), the scattered electric field may be written as:

$$\boldsymbol{E}_s = Af(r)\, E_0(r) \exp(i\boldsymbol{k} \cdot \boldsymbol{r}_0 - i\omega t) \qquad \ldots (11)$$

Here $\omega = \omega_0 + \Delta\omega$ and $\Delta\omega = \boldsymbol{K}.\boldsymbol{v} = |K|\,|v| \cos\theta$, θ being the angle between the scattering vector $\boldsymbol{K}$ and the particle velocity vector $\boldsymbol{v}$. In many cases, it can be conveniently arranged for backscattered light to be detected where the initial laser beam and the scattered light are in opposite directions. Thus $\boldsymbol{k}_s = -\boldsymbol{k}_i$ and $\Delta\omega$ may be written as:

$$\Delta\omega = 2\,|\,k_s\,|\,|\,v\,| \cos\theta \qquad \ldots (12)$$

As $k_s = 2\pi n/\lambda$, where n is the refractive index of the medium and λ is the wavelength *in vacuo*, then:

$$\Delta\omega = 4\pi n\, v \cos\theta/\lambda \qquad \ldots (13)$$

The angle θ is now the angle between the flow and the direction of the incident laser beam. It should be noted that a fibre-optic device introduced into a flowing medium may well collect light scattered in directions other than exact backward scattering, particularly near the fibre-optic exit. However, this can be minimised by the use of apertures in the collection optics, when only light collected in a small solid angle around the backward direction is collected.

One of the most interesting applications of optical techniques is in the field of blood flow measurement *in vivo*. A number of different techniques have been applied in recent years to the measurement of the flow of blood in living organisms (Roberts, 1982). A range of flow velocities from 1 to 10^{-4} m/s is encountered and, as a consequence, no one technique is universally applicable. Such methods as the electromagnetic flow meter and Doppler ultrasonics have been used, primarily for the measurement of flow in major vessels. The use of radioisotopes has a particular application where measurement in whole organs or capillaries is needed. Optical methods have recently been applied (Nilsson *et al*, 1982) and laser Doppler flowmetry seems to overcome many of the disadvantages associated with other methods. It can, under certain circumstances, facilitate continuous and non-invasive measurement of blood flow to the capillary level.

The Laser Doppler technique has been applied by Yeh and Cummings (1964) to measure the flow velocity and velocity profile of a dilute colloidal suspension in a large-diameter tube and resolve velocities down to 0.007 cm/s. Riva *et al* (1972) first applied the technique to blood flow through

200 μm capillary tubes and to the retinary artery of a rabbit to yield information on the velocity distribution of the flow, as well as the average velocity. This approach, using light from a $\lambda = 632.8$ nm He-Ne laser, did not require mechanical perturbation or chemical alteration of the environment. Subsequently Tanaka *et al*, (1974) made similar measurements on human retinal vessels. The fibre-optic approach was developed by Tanaka and Benedek (1975) to measure flow in the femoral vein of a rabbit by the use of a 500 μm optical fibre inserted into the flow. Further work by Watkins and Holloway (1978), again using 632.8 nm laser illumination, developed a non-invasive technique to measure cutaneous blood flow by monitoring the non-shifted reflection from the skin as well as the frequency shifted reflection from the flowing blood cells at a depth of ~ 1 mm. An average value was obtained for the flow velocity using a ~ 150 μm transmitting fibre and ~ 750 μm receiving fibre. The authors commented that the laser power used was 'about the lower limit necessary'. A higher-resolution device has been developed recently by Nishihara *et al* (1982) using a 150 μm optical fibre. The system claims high temporal (8 ms) and spatial (~ 100 μm) resolution as well as the general advantages of fibre techniques. However, it is an invasive technique and there is some disturbance of the blood flow, as measured in the femoral and coronary arteries of mongrel dogs, by the presence of the fibre, inserted into blood vessels through the centre of a hypodermic needle. Cochrane and Earnshaw (1978) have used the laser Doppler velocimeter to measure fluid flow in narrow vessels of varying widths (60–380 μm) and obtained flow profiles across the vessel. This work was extended to measure the velocity of blood flowing in microvessels (Cochrane *et al*, 1981) *in vitro* and *in vivo* in the web of the foot of a frog, where the vascular system was readily accessible. Signal analysis of the scattered ~ 1 mW 632.8 nm laser light was carried out by digital photon correlation, the Doppler information having been obtained from the autocorrelation function of the scattered light. The recent non-invasive work by Nilsson *et al* (1980a, b) measured blood flow in the forearm and finger using a central transmitting fibre surrounded by an array of fibres to collect the scattered light. This multi-channel approach enables a greater sensitivity of detection to be obtained in a differential amplifier through the rejection of common components such as laser and environmental noise without the overall blood-flow related signal being rejected. A recent simple fibre-optic relative blood flow monitor for use in triggering more sophisticated heart monitoring equipment has been designed by Shah *et al* (to be published). Operating at 0.85 μm in a non-invasive mode, it monitors the light reflected from blood flowing in the jugular vein, such light being received by a fibre-optic bundle surrounding a central transmitting fibre. Good depth penetration is achieved.

The field of Doppler blood flowmetry is still open for a study which can extend its applicability and accuracy. In principle, flow velocities in the range experienced clinically can be measured without surgical exposure of the vessel. The active part of a laser/fibre optic device could be smaller than an ultrasonic Doppler transducer, for convenience of operation. Indeed the use of smaller optical fibres than have been presently employed (~ 150 μm) is possible, thereby minimising disturbance of flow in an invasive technique and offering higher spatial resolution in both invasive and non-invasive applications. This could give more information on the velocity distribution across larger vessels. The non-invasive technique is the most valuable, for obvious reasons, but the use of laser radiation in the red at 632.8 nm imposes severe limitations upon the depth of study, bearing in mind the limit on human skin illumination power of 2 mW/mm^2 set by European safety standards. The penetration depth is determined by the value of scattering and absorption coefficients of tissue and blood. Factors such as pigmentation (Jacquez *et al*, 1955), blood volume and degree of haemoglobin oxygenation (Mohapatra and Smith, 1975) can influence the penetration depth of light in tissue as shown in Figs 15 and 16. The skin becomes relatively transparent in the near IR region (Mohapatra and Smith, 1975), and white and black skins have essentially the same optical characteristics as the melamin pigment has no significant effect on transmittance or reflectance in the IR. Beyond 1.4 μm, water absorption is dominant. The use of the techniques described, coupled with lasers operating in the IR region ($\lambda > 0.7$ μm) (e.g, IR dye lasers, or on IR He-Ne transitions, or cw semiconductor lasers) opens the way for a non-invasive blood flow study at greater penetration depths and with greater spatial accuracy than has been achieved. It is fortunate that much work has been done in designing fibre-optic components for operation in these near IR regions for communications purposes (Li, 1983), to produce very low loss and readily available fibres of diameters down to a few micrometres into which coherent laser radiation can be launched.

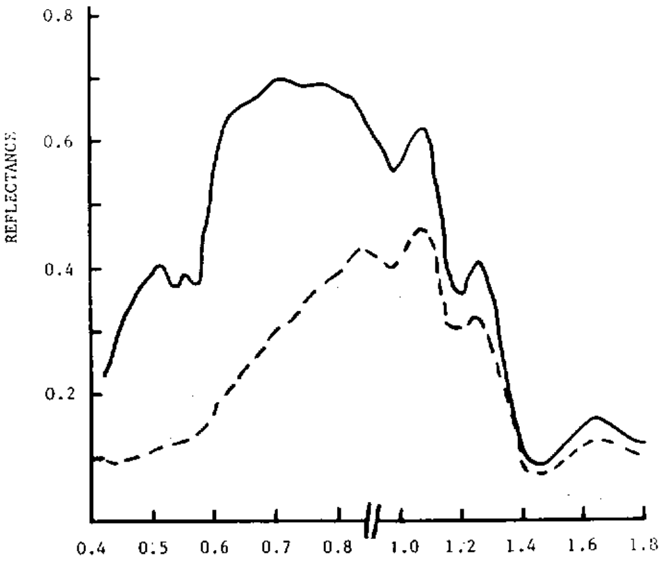


Fig 15 Comparison of skin reflectance of very fair complexioned subject (solid) and very dark subject (dashed)

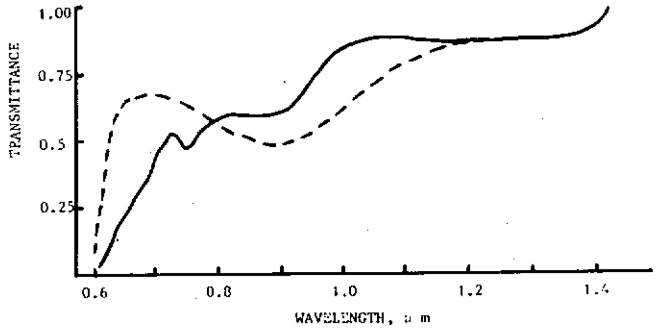


Fig 16 Transmission of whole ox-blood. Solid line– reduced blood (oxygen saturation below 8%). Dashed line – oxygenated blood (oxygen saturation above 97%)

Conclusion

This paper has presented a summary of some of the available techniques for a range of fibre-optic sensors. As may be noted from the dates of publication of the references, most devices have been discussed within the last few years, and the field continues to expand with projections for future use and market penetration encouraging (Giallorenzi *et al*, 1982; Jones, 1981b). As the use of optical multiplexing techniques expands, it will facilitate the wider employment of various optical sensors, linked to a common cabling network.

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